An Experimental Study on Engineering Properties of Bentonite - Sand Mixtures

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An Experimental Study on Engineering Properties of Bentonite - Sand Mixtures

Thesis submitted in partial fulfillment

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in

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by

Rongala Siva Naga Srikanth

(Roll Number: 215CE1020)

based on research carried out

under the supervision of

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Department of Civil Engineering

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Certificate of Examination

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We the below signed, after checking the thesis mentioned above and the official record book(s) of the student, hereby state our approval of the thesis submitted in partial fulfillment of the requirements for the degree of Master of Technology in Geotechnical Engineering at National Institute of Technology Rourkela. We are satisfied with the volume, quality, correctness, and originality of the work.

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Supervisor's Certificate

This is to certify that the work presented in the thesis entitled "***An Experimental Study on Engineering Properties on Bentonite-Sand Mixtures**,*" Roll Number 215CE1020, is a record of original research carried out by him under my supervision and guidance in partial fulfillment of the requirements for the degree of *Master of Technology in Geotechnical Engineering*. Neither this thesis nor any part of it has been submitted earlier for any degree or diploma to any institute or university in India or abroad.

Prof. Ramakrishna Bag
Assistant Professor

Dedicated to my lovable parents and my brother

Declaration of Originality

I, *Rongala Siva Naga Srikanth*, Roll Number *215CE1020* hereby declare that this dissertation entitled *"An Experimental Study on Engineering Properties on Bentonite-Sand Mixtures"* presents my original work carried out as a Master student of NIT Rourkela and, to the best of my knowledge, contains no material previously published or written by another person, nor any material presented by me for the award of any degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the sections "Reference". I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

I am fully aware that in the case of any non-compliance detected in future, the Senate of NIT Rourkela may withdraw the degree awarded to me on the basis of the present dissertation.

May 29, 2017

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Abstract

For the past few decades, compacted bentonite has been considered as potential buffer material in toxic waste disposal repositories because of its low permeability and high swelling capacity. Bentonite has been mixed with sand in appropriate proportions to make bentonite-sand mixtures that are used as backfilling material to seal the galleries of high-level toxic waste disposal repositories. The permeability of barrier should be in the range of 10^{-8} to 10^{-10} m/s in the saturated condition. Bentonite from used Bikaner, Rajasthan and local river sand in Rourkela are used for this study.

The maximum dry density and optimum moisture content of bentonite-sand mixtures were determined with variation in bentonite content of 10, 20, 25, 30, 40 and 50% in total weight of the mixture. The permeability of bentonite-sand mixtures was determined using falling head method. For the mixtures having permeability value less than 10^{-9} m/s, consolidation tests were conducted to find permeability indirectly and to check the permeability values with falling head method results. Based on the permeability results swelling pressure and unconfined compression strength tests were conducted on bentonite-sand mixtures having permeability range of 10^{-8} to 10^{-10} m/s in the saturated condition. The test results show that the permeability value decrease where as swelling pressure increases with the increase in bentonite content. The maximum unconfined compressive strength was found for 40% bentonite-sand mixture.

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Chapter 1

Introduction

1.1 Background

This chapter explains the advantages and uses of bentonite-sand mixtures in the field, which provides the objectives of the present work. The environmental pollution due to leakage of waste from waste repositories is a well-known problem in the present world. For the last few decades, there was a common practice of mixing sand with sufficient amount of bentonite to make bentonite-sand mixtures as construction materials used in engineering applications such as hydraulic and waste containments. The design of repositories depends on the waste to be disposed of. Waste containing toxic materials can be disposed of safely by designing suitable barrier. The main aim of designing barrier is to reduce the contact between waste and host environment. These barriers should restrict radionuclides release to the environment if waste material to be disposed of is radioactive. To achieve the required properties of the barrier, the soil used for barriers should have low permeability, less shrinkage on drying, less susceptible to frost damage, more strength and more volume stability. The permeability of soil mixtures used for barriers must be less than 10^{-9}m/s. The main advantage in using bentonite-sand mixtures is low permeability due to highly swelling nature of bentonite. The bentonite particles swell and fill the voids present in between the sand particles thereby permeability decreases. Another advantage is low compressibility due to sand particles framework. The bentonite-sand mixtures are very less susceptible to frost damage than natural clay (Dixon and Gray 1985) and less shrinkage on drying.

Bentonite clay is highly expansive clay containing a large amount of montmorillonite mineral. It possesses high swelling and shrinkage properties because of the montmorillonite mineral. Bentonite mixed with coarse soil such as sand will the reduce shrinkage and compressibility and increase strength and stability of the mixture. Advantages of using bentonite-sand mixtures in place of natural clay for the barrier is that it has less shrinkage on drying and less susceptible to frost damaging. On drying, bentonite voids ratio decreases, which bring sand particles to contact thereby preventing more shrinkage and providing high strength.

Bentonite sand mixtures used as barrier materials for many engineering applications, which includes waste containments like a landfill, cores of the earthen dam, cut-off walls, and buffer and backfill material for radioactive waste containments. They are also used as the hydraulic containments in reservoirs. Bentonite content in the bentonite-sand mixture is the prime criteria of buffer material that should be taken into consideration in designing any waste disposal facilities.

1.2 Field applications

In the past, one of the causes of the soil and environmental pollution is the disposal of solid waste in open dumps. These waste disposals migrate to underground soil and pollute the soil and environment around it. Because of this type of pollution, human and animal health is also affected. Therefore landfills with isolated liners were developed. There are different types of liners used like bentonite sand liners, compacted clay liners, and geosynthetic clay liners. Bentonite sand liner is one of the types of liners, which is commonly used in the field. Many research studies were done in landfill topic (Chapuis 1990; Sivapullaiah et al. 2000; Akgün et al. 2006). Bentonite sand mixtures also used for slurry cut-off walls, which used for isolating the existing landfill and contaminated soils to prevent the spreading of contaminants to the environment (Ryan 1985; Evans 1993). Radioactive waste materials disposal depends on level or intensity of waste to be disposed of. They are four levels of radioactive waste: high-level waste, intermediate level, low-level waste and very low-level waste. Bentonite sand mixtures are majorly used as buffer and backfill materials in the radioactive waste disposal process.

1.3 Objectives

The objective of the study is to investigate the suitability of bentonite-sand mixtures as barrier/liner material for waste and hydraulic containments. To achieve the objective hydromechanical properties of bentonite-sand mixtures are analyzed which includes

(a) Determination of change in permeability of bentonite-sand mixtures with a change in bentonite content using the falling head method and consolidation method.

(b) Determination of swelling pressure using modified odeometer and strength characteristics for bentonite-sand mixtures with a change in bentonite content.

1.4 Thesis Overview

The total thesis divided into five different chapters.

Chapter 1: This chapter gives introduction, advantages, and uses of bentonite-sand mixtures as engineering barriers. Objectives and overview of the thesis presented.

Chapter 2: The Literature review of different characteristics of bentonite-sand mixtures presented in this chapter.

Chapter 3: Materials used and methods followed to achieve the objectives of project work presented in this chapter.

Chapter 4: Presents the results obtained from compaction, permeability, swelling pressure and unconfined compression strength tests for different bentonite-sand mixtures and analysis of results.

Chapter 5: Overall conclusion from the results and scope of the further study.

Chapter 2

Literature review

2.1 Introduction

The literature review of engineering characteristics of bentonite-sand mixtures used in the engineering applications as cut-off walls, landfill liners, and buffer and backfill materials for radioactive waste disposal discussed in this chapter. There is a lot of research work related to compaction, permeability, swelling and strength characteristics of the bentonite-sand mixtures. The design of liners/barriers depends on the waste and contaminated site (Alther 1987). Alther (1987) given criteria for designing of liners. They are (a) facility type, (b) type and quantity of waste, (c) location of the site and (d) life for the facility. The barriers are provided to prevent the mobility of contaminants, which can be achieved with low permeability. Different type of materials like compacted clay, soil-bentonite, geotextiles and geomembranes used for liners/barriers (Sällfors & Öberg-Högsta 2002). Bentonite consists of smectite minerals shown in figure 2.1, which has montmorillonite in structure. Because of smectite minerals presence in bentonite, it has high swelling nature, low permeability, high specific surface area and cation exchange capacity (Gleason et al. 1997). Depends on the type of external cations bentonite is two type’s sodium bentonite and calcium bentonite. Sodium bentonite has lower permeability and higher swelling values compared to calcium bentonite, so its applications are more in engineering barriers/liners (Alther 1982; Reschke and Haug 1991). For a particular void ratio, calcium presence smectite had 1000 times more permeability compared to sodium presence smectite (Mesri and Olson 1971). Sand has a higher percent of quartz mineral. Mixing of bentonite and sand at particular ratios will produce a mixture of low permeability, less shrinkage on drying, less susceptible to frost damage, more strength and more volume stability. There are some requirements have to be fulfilled by bentonite-sand mixtures used as engineering barriers/liners which mainly depends on hydro-mechanical characteristics of bentonite-sand mixtures (Chapuis 1990; Parker et al. 1993; Thériault 2000; Gueddouda et al. 2008). They are

(a) The thickness of bentonite-sand barriers should be in the range of 15 to 30 cms.

(b) The permeability of barrier should be in the range of 10^{-8} to 10^{-10} m/s in the saturated condition.
(c) The stability of barrier should not be effected because of water in wet conditions.
(d) Swelling ability must be higher enough to fill cracks in host rocks to have more stability.

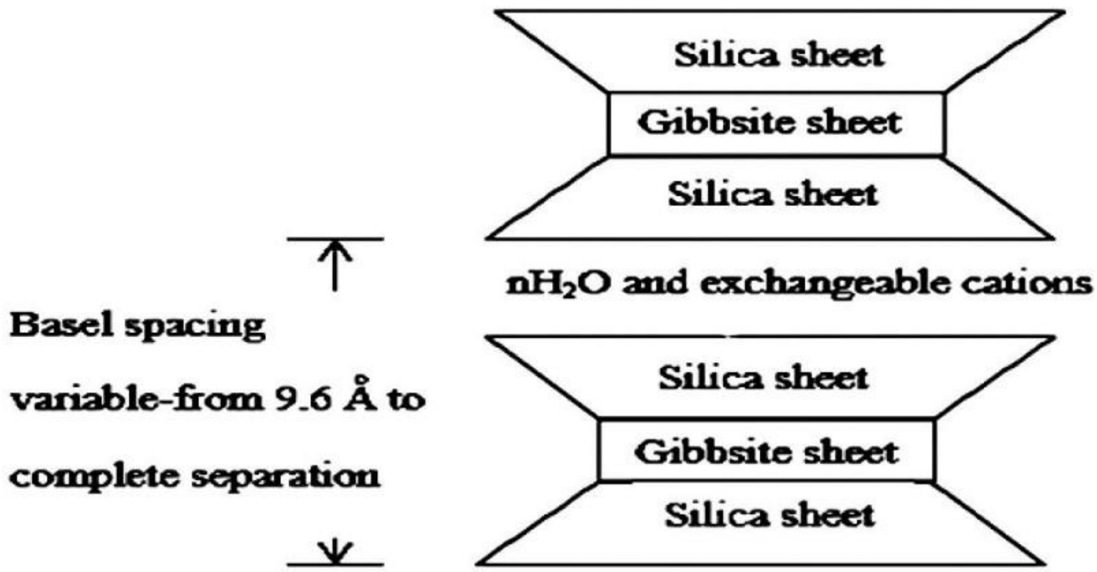

Figure 2.1: Diagram of the montmorillonite structure (Das 2013)

2.2 Compaction characteristics of bentonite-sand mixtures

Soil compaction is a process of increasing density of soil by reducing voids between the soil particles using mechanical energy. A lot of literature is available regarding compaction of bentonite-sand mixtures. The effect of bentonite content, compaction effort and curing period on maximum dry density (MDD) and optimum moisture content (OMC) is described in this section.

Kenney et al. (1992) conducted a list of standard proctor tests on different bentonite-sand mixtures using distilled water with variation in bentonite percent as 4%, 8%, 12%, 16% and 22%. They also used two methods for mixing of materials in a particular proportion. The first method was mixing bentonite and sand in dry conditions and then adding water, while the second one was mixing dry bentonite with wet sand and then adding water to it. They found that there is no variation in results using two methods of mixing. They found that with the increase in bentonite content up to 20% caused an increase in maximum dry density (MDD) and there is a decrease in maximum dry density (MDD) beyond 20%.

Howell et al. (1997) examined the effect of variation in curing period, different types of clay soil and using different mixing methods on compaction behavior of sand attapulgite clay, sand granular bentonite, and sand powdery bentonite mixtures. Curing periods used are one day and seven days. Clay soil percentages used in mixtures are 10%, 15%, and 20%. Two mixing methods were used for the study. They are (i) mixing bentonite and dry sand before adding water and (ii) mixing dry sand and water before adding bentonite. The compaction test results for the three mixtures with increasing bentonite content shown in Table 2.1.

Table 2.1: Change in maximum dry density and Optimum moisture content with increase in bentonite content (Howell et al. 1997)

Type of soil mixture	Maximum dry density (MDD) with increasing bentonite content	Optimum moisture content(OMC) with increasing bentonite content
Sand attapulgite clay	Decrease	Increase
Sand granular bentonite	Relatively constant	Decrease
Sand powdery bentonite	Increase	Decrease

Howell et al. (1997) found that attapulgite clay has higher water sorptivity and lower swelling potential compared with the other two clays and granular bentonite has more amount of large size particles compared to powdery bentonite are the two reasons for the peculiar behavior of the three mixtures. They found that first mixing method gives higher maximum dry density (MDD) and optimum moisture content (OMC) than second. They also found a small effect on maximum dry density (MDD) and optimum moisture content (OMC) due to two curing periods.

Chalermyanont and Arrykul (2005) conducted standard compaction tests on bentonite-sand mixtures with varying bentonite percent as 0, 3, 5, 7 and 9%. They found that as the bentonite percent increases in the mixture its maximum dry density decreases and optimum moisture content increases as shown in Figure 2.2.

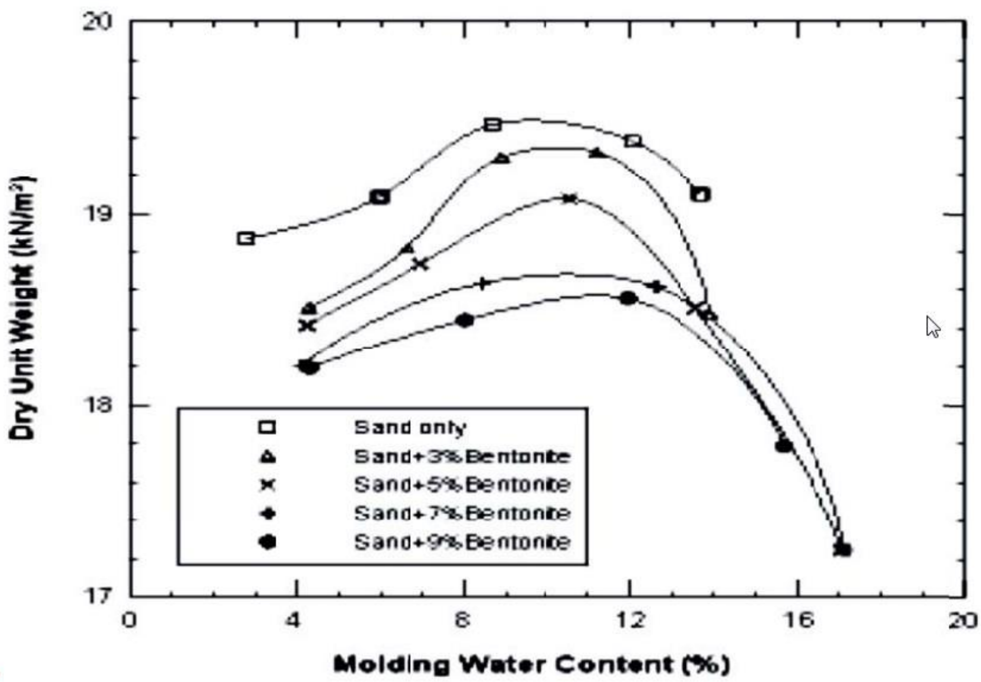

Figure 2.2: Compaction curves for different bentonite-sand mixtures (Chalermyanont and Arrykul 2005)

Akgün et al. (2006) performed compaction tests on three bentonite-sand mixtures with variation in bentonite content as 15, 17.5 and 20%. After the tests, they found that maximum dry density decreases and optimum moisture content increase with an increase in bentonite percent in bentonite-sand mixtures. The results are shown in Table 2.2.

Table 2.2: Compaction tests results for different bentonite-sand mixture (Akgün et al. 2006)

Bentonite content (%)	Maximum Dry Density (kN/m^3)	Optimum moisture content (%)
15	16.01	15.82
17.5	15.41	16.24
20	15.10	16.29

Amadi and Eberemu (2012) conducted compaction tests on mixtures with 0, 2.5, 5, 7.5 and 10 % lateritic bentonite soil with different compaction energies. The compaction energies used are Reduced British Standard Light, British Standard Light, West African Standard and British Standard Heavy. They found that for all the compaction energies there is a decrease in maximum dry density and increase in optimum moisture content with the increase in bentonite content in the mixture as shown in Figures 2.3 and 2.4.

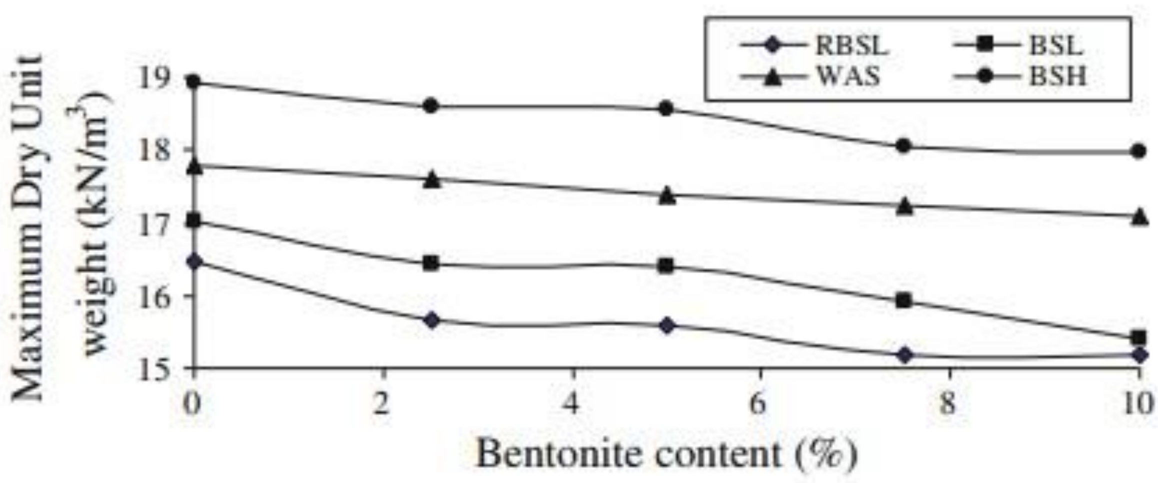

Figure 2.3: Maximum dry density versus bentonite content (Amadi and Eberemu 2012)

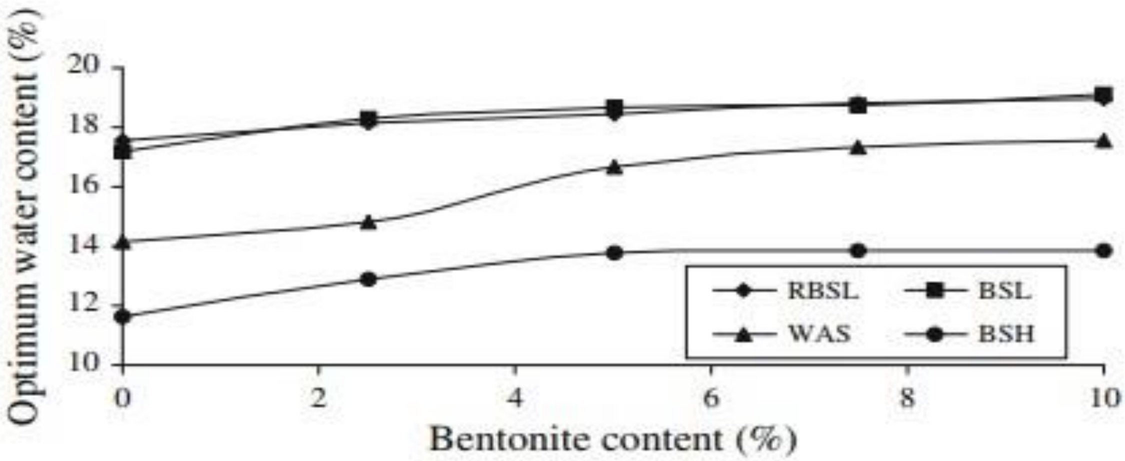

Figure 2.4: Optimum moisture content versus bentonite content (Amadi and Eberemu 2012)

2.3 **Permeability characteristics of bentonite-sand mixtures**

The property that is very important in the design of liners or barriers is permeability. Permeability characteristics of bentonite-sand mixtures and factors affecting it for the use of waste repositories studied in the various literature. Some of the factors affecting permeability characteristics of bentonite-sand mixtures are bentonite type (Mitchell and Soga 1976), bentonite percent (Chapuis 1990; Chalermyanont and Arrykul 2005;

Gueddouda et al. 2008), particle size distribution (Chapuis 1990; Sivapullaiah et al. 2000), swelling properties (Studds et al. 1998; Komine 2008; Shirazi et al. 2010), compaction water content (Kenney et al. 1992), type of permeant liquids (Kenney et al. 1992; Studds et al. 1998) and degree of saturation (Chapuis 1990).

Lee et al. (1994) conducted permeability tests on clay aggregates mixtures. Clay used was calcium bentonite from Kampo and aggregate used was crushed granite from Daeduk. They studied the dry density moisture content relationship to define an optimum moisture content that gives maximum attainable dry density at constant compaction pressure. They also analyzed permeability as a function of clay content present in the mixture. They found that at a particular dry density of 1.2 Mg/m^3 permeability of mixture increased from $7*10^{-10}$ m/s to $5*10^{-12}$ m/s with clay content increasing from 25% to 100% by weight. They suggested the effective clay dry density concept find the permeability of mixtures with different dry density and different crushed rock content.

Mollins et al. (1996) conducted four different methods to find permeability of bentonite-sand mixtures. Methods used were Rowe cell constant head tests, falling head tests, standard compaction permeameter and consolidation tests. Bentonite percent of 5, 10 and 20% were used in the mixtures with distilled water as pore fluid. They found there was a linear relation between void ratio and the logarithm of effective vertical stress for all bentonite contents at a particular effective stress. They also found that low bentonite percent use in mixtures caused uneven bentonite distribution in the mixture.

Gleason et al. (1997) conducted permeability tests on bentonite-sand mixtures to find the variation in permeability with a change in bentonite type. For analysis, two types of bentonites considered namely sodium bentonite and calcium bentonite. Three types of sand used were group A (medium and uniform sand), group B (broadly graded sand) and group C (silty sand). These three types of sand classified as SP, SW, and SM respectively. Bentonite percent used were 6, 12, 20 and 30%. Permeability test for these mixtures conducted in two ways. One way was specimen permeated with tap water and after that with a 0.25M $CaCl_2$ solution. Second-way specimen permeated with 0.25M $CaCl_2$ solution only. After the experiments, they found that second way of permeating specimen gave higher permeability than first. Results obtained indicated that to have permeability value less than $1*10^{-9}$ m/s calcium bentonite amount needed should be three times more than the sodium bentonite.

Borgesson et al. (2002) conducted permeability tests for bentonite ballast materials (crushed rocks) with bentonite varying from zero to 50%. They found permeability of bentonite ballast materials mixtures had higher permeability than bentonite alone because of uneven bentonite distribution in mixtures.

Komine (2010) compared the results obtained from the permeability tests conducted on the bentonite-sand mixture with varying bentonite content as 10, 20, 30 and 50% with the results obtained from theoretical equations developed by Komine (2008). Komine (2010) suggested the applicability of the equation for finding the permeability of bentonite-sand models with certain limitations because of having some chemical parameters, which had to be estimated using highly developed procedures and equipment.

Siddiqua et al. (2011) found the pore fluid impact on the permeability of repositories. Repositories examined were (a) dense backfill material composed of crushed granite (75%), glacial lake clay (18.75%) and Avonlea bentonite (6.25%) and (b) light backfill material composed of sodium bentonite (50%) and silica sand (50%). They found that with an increase in the montmorillonite density permeability of mixtures decreased. They also found that specimen saturated with saline water had higher permeability value than those with distilled water.

Watabe et al. (2011) conducted odometer tests on bentonite-sand mixtures to know the effect of bentonite-sand fractions on the permeability. They found that permeability increased significantly with increase in sand fraction.

Fan et al. (2014) performed one-dimensional consolidation tests on bentonite soil and bentonite-sand mixtures to find the influence of sand and water content on the permeability. They found that permeability was highly influenced by bentonite content because permeability decreased with increase in bentonite content.

2.4 Strength characteristics of Bentonite-Sand Mixtures

The strength characteristics of bentonite-sand mixtures as engineering barriers is one of the important parameters to check the long life stability of the structure. Irrespective of different chemical composition and particle size distribution of bentonite and sand, their mixture gives lower permeability and higher strength. Coulomb in the 18th century first studied the strength characteristics of sand (Das 1983). After many years' strength characteristics of clay were found (Wasti and Alyanak 1968). Wasti and Alyanak (1968) given the relation between clay percent and atterberg limits in clay-sand mixtures. They found that if a sufficient number of clay particles are present in the mixture to fill the voids present then the behavior of mixture changes to clay from sand. Cho et al. (2002) studied literature to find unconfined compression strength test and young's modulus of elasticity of bentonite-sand mixtures with variation in dry density, moisture content, and sand content. They tested mixtures for using as buffer material in high-level radioactive repositories. They found that as the sand percent in mixture increased unconfined compression strength and young's modulus decreased.

2.5 Swelling pressure characteristics of Bentonite-Sand Mixtures

Swelling pressure is the pressure required to maintain constant volume condition when water is added to an expansive soil. There are three different tests for testing swelling pressure of expansive soil samples suggested by Sridharan et al. (1986). They are (a) constant volume test; (b) swell under load test and (c) swell load test. ASTM D 4546 (ASTM, 1997) describes the swelling pressure test using oedometer. The increase of swelling pressure and absorbed water decreases asymptotically after a certain time, which shows the end of primary swelling pressure. Gattermann (1998) found that swelling pressure value remains same with time once it reaches the maximum. Alonso et al. (1999) found the decrease in swelling pressure value due to macro structure collapse of clay. Therefore swelling pressure value may increase, decrease or remain constant with time once it reaches maximum primary swelling pressure. Nevertheless, after reaching maximum swelling pressure, swelling pressure increasing rate will be decreased.

Holopainen (1985) performed the swelling pressure tests for bentonite crushed aggregate mixtures of different proportions of backfill materials with distilled and saline water. They reported that lowest swelling pressure case found when distilled water used for compaction and saline water for testing. Therefore, to avoid less swelling pressure distilled water not used when groundwater is saline. Studds et al. (1998) conducted swelling pressure on bentonite-sand mixtures with bentonite variation of 10 and 20% by dry weight using distilled water and different salt solutions of 0.01, 0.1 and 1 mol/l concentrations. They found the swelling property of bentonite-sand mixtures depends on applied stress, pore fluid used and clay percent. Swelling behavior of bentonite and load deformation behavior of sand are used to find the swelling behavior of bentonite-sand mixtures. At lower effective stresses, they found bentonite-sand mixtures behavior is same as bentonite. At higher effective stresses bentonite-sand mixtures behavior differs from bentonite alone. For 20% bentonite mixture, swelling results using distilled water and 0.01 mol/l salt solution are same.

Komine and Ogata (2003) found that swelling pressure is highly influenced by bentonite percent in bentonite-sand mixtures in addition to initial dry density and vertical pressure during the test. Cui et al. (2012) performed laboratory tests on swelling pressure of bentonite-sand mixtures with varying sand percent in the mixture as 0, 10, 20, 30, 40 and 50% by weight. They found that with constant initial moisture content the maximum swelling pressure value of bentonite-sand mixtures showed an exponential increase. They also found that with the increase in sand percent in bentonite-sand mixtures swelling pressure decreased exponentially. Zhang et al. (2012) conducted swelling pressure tests on bentonite and bentonite-sand mixtures with variation in sand content as 0, 20, 30 and 50% using distilled water and $NaCl$-Na_2SO_4 solutions of 0.5, 1, 3, 6 and 12 g/l concentrations. They found the maximum swelling pressure value decreased linearly with the increase in $NaCl$-Na_2SO_4 concentration. They also found with the change in $NaCl$-Na_2SO_4 concentration the maximum swelling pressure values of bentonite-sand mixtures showed very less alteration compared with bentonite alone. Therefore, bentonite-sand mixtures have relatively better resistance to chemical attack. Sun et al. (2013) found that at full saturation the relationship between void ratio and swelling pressure of GMZ bentonite-sand mixtures was dependent only on bentonite and sand contents in the total mixture and independent of initial dry density and moisture content. They gave an empirical formula to find a relation between dry density and swelling pressure at different bentonite and sand ratios.

Chapter 3
Material and Methods

3.1 Introduction

This chapter describes the soils used, their properties and the methods followed to achieve the objectives of the project. The soils used in this project are bentonite clay from Bikaner Rajasthan and sand from Rourkela, Odisha. Bentonite used is in dry powder form with a natural moisture content of nearly 11%. Compaction, permeability, unconfined compression strength and swelling pressure tests conducted on bentonite-sand mixtures to find the usage of these mixtures as engineering barriers.

3.2 Properties of Bentonite

Physical properties like atterberg limits, specific gravity, natural moisture content, particle size distribution, mineralogical composition, specific surface area, clay content and soil classification of bentonite are determined.

The liquid limit and plastic limit of bentonite soil are determined using the methods described in IS 2720 Part 5 (1985). IS 2720 Part 6 (1972) is used for finding shrinkage limit of bentonite. These Atterberg limits found used to study the plastic properties of bentonite soil. Liquid limit test for bentonite soil by the mechanical method is very difficult, so cone penetration method is used. The test conducted until penetration value is obtained between 20 mm and 30 mm. Plastic limit is obtained by preparing standard bentonite threads of 3mm diameter before the beginning of crumble. Plasticity index used for the soil classification in the difference between liquid limit and plastic limit. For the shrinkage limit, bentonite soil is mixed with distilled water slightly more than the liquid limit and placed in a greased shrinkage dish. Weight measurements were done until no further reductions noted. Differential free swell and linear shrinkage of bentonite soil is determined by the methods described in IS 2720 Part XL (1977) and IS 2720 Part 20 (1992) respectively.

The natural moisture content (or) hygroscopic water content is the water content that is present in the soil when the soil is in the equilibrium condition with the atmosphere having a relative humidity of 50% at the temperature of 20 °C and do not evaporate at ambient temperature. Natural moisture content is obtained by oven drying soil sample at 105 °C for

24 hours as described in IS 2720 Part 2 (1973). The quantity of water adsorbed depends on cations present in soil and specific surface area (Mitchell 1993). The natural moisture content of bentonite is 11%.

The specific gravity of soil is determined using pycnometer method as described in IS 2720 Part 3 (1980). Specific gravity calculation using water in high montmorillonite content clays like bentonite is difficult because of its high swelling nature and incomplete penetration of water inside the soil particles (Grim 1968). For that reason, non-polar liquid like kerosene is used to find the specific gravity of bentonite soil.

There are different methods to find the specific surface area of clay according to the dry or wet condition of the soil sample. Specific surface area method used for bentonite in this study is for the determination of dry condition using nitrogen gas adsorption using Brunauer Emmett-Teller isotherm method (Grim 1968). The only external surface area is found using Brunauer Emmett-Teller (BET) isotherm method. The range for the external surface area of montmorillonite particles is from 39.8 to 120 m^2/g (Alymore et al. 1969). All physical properties are presented in Table 3.1.

The particle size distribution of fine-grained clayey soils is determined using settling rate of particles in liquids following Stokes law (Lambe and Whitman 1969). The method used is hydrometer analysis 2720 Part 4 (1985). For the analysis take 50 grams of oven-dried soil passing through 75-micron IS sieve. Prepare dispersing agent by adding 33 grams of sodium hexametaphosphate and 7 grams of sodium carbonate in 1000ml solution. Add 100 cc to soil with some distilled water, and allow it to soak for few hours. Add distilled to two third the beaker and stir the solution for 15 minutes. Now transfer the total soil mixture in 1000 cc standard measuring jar and make the suspension 1000 cc by adding distilled water. Draw the calibration curve for the hydrometer and find the hydrometer corrections. Insert hydrometer inside the suspension and start the stopwatch. Take the readings accordingly. Test results are shown in figure 3.1.

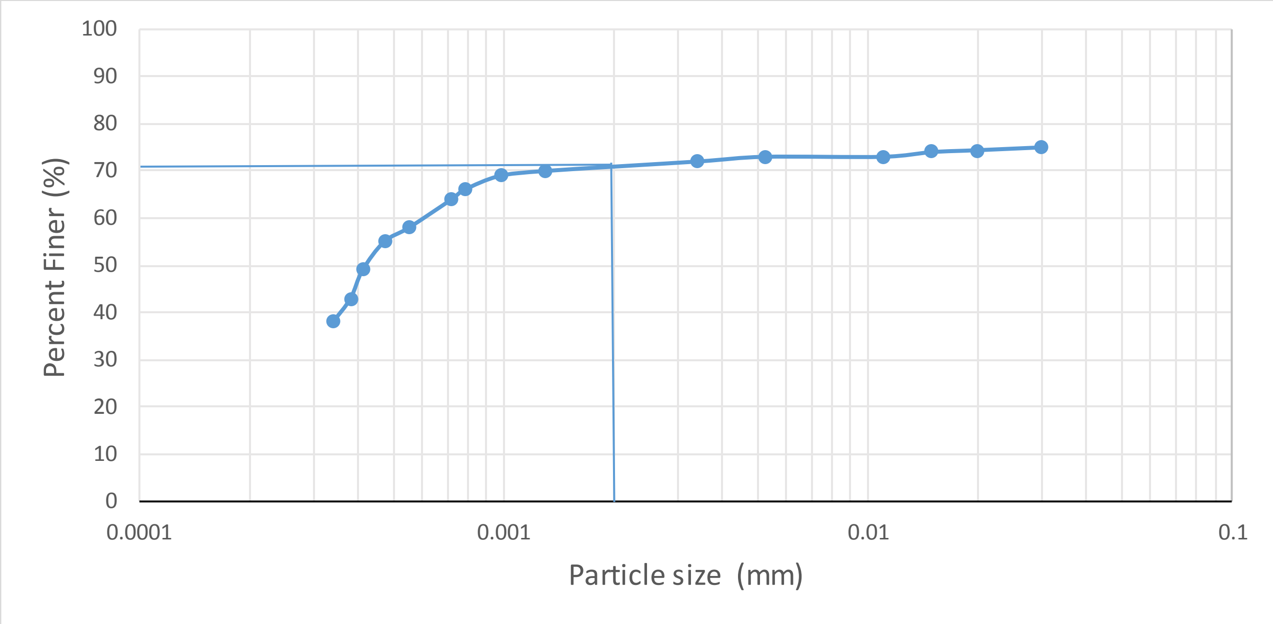

Figure 3.1: Grain size distribution curve of Bentonite

Table 3.1: Properties of Bentonite

Properties of Bentonite Soil	**Value**
Liquid Limit (%)	139
Plastic Limit (%)	50
Plasticity Index I_P (%)	89
Shrinkage Limit (%)	38
Specific Gravity	2.70
Clay Content C (%)	71
Activity Number = (I_P/C)%	1.25
Differential Free Swell (%)	150
Natural Moisture Content (%)	11
Specific Surface Area (using BET Method) (m^2/g)	71.79
Group Symbol(IS Soil Classification System)	CH

3.2.1 XRD Analysis

X-ray diffraction analysis used to study the mineralogical compositions of clays (Grim 1968; Mitchell 1993). Rigaku source and Philips power diffractometer with Cu Kα radiation at 35 kV and 40 mA used for conducting the test. Five grams of oven-dried bentonite passing through 75 microns is tested. In XRD analysis, minerals in soil are identified by relating incidence ray angle of X-rays with its spacing of c-axis. XRD pattern is obtained by scanning the soil sample ranging from 0 to 90° over an angle 2θ at a scanning rate of 5°/minute. Setting 2θ less than 5° will damage detector and more than 140° will make X-ray source and detector to collide. The minerals found in bentonite through X-ray diffraction analysis shown in Figure 3.2 are Hematite, Fluorite, Sodium Erbium Fluoride, Alumina, Calcite, Quartz and Montmorillonite.

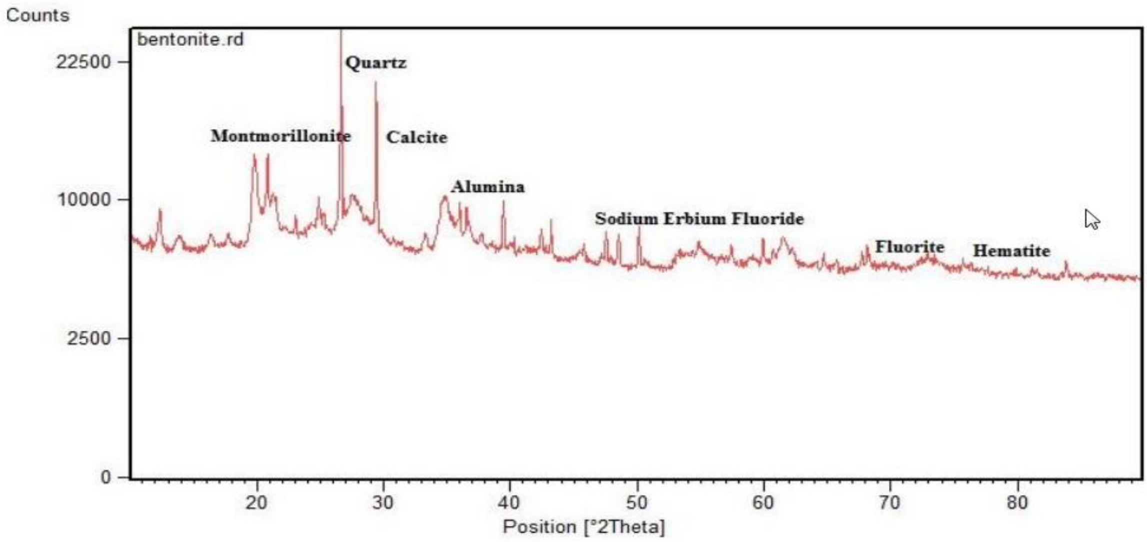

Figure 3.2: XRD Analysis of bentonite soil

3.2.2 SEM Analysis

Scanning electron microscope analysis gives configuration of the sample, particle boundary relationships, and texture of crystals. Scanning electron microscope Figure 3.3 of bentonite soil is shown below. From the figure, it was found that a lot of small size particles are present in bentonite soil.

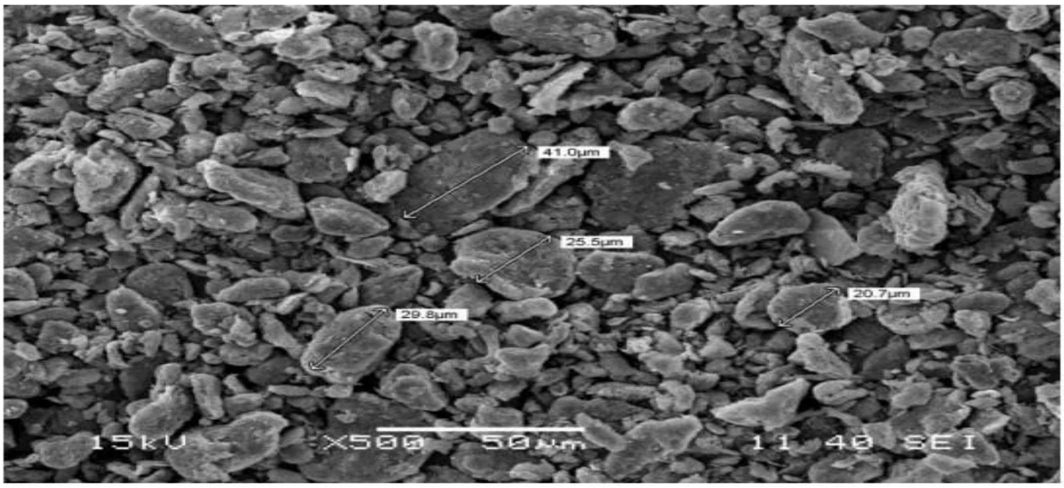

Figure 3.3: SEM Analysis of bentonite soil

3.3 Properties of sand

The physical properties and particle size distribution of sand used shown in Table 3.2 and Figure 3.4. According to unified soil classification system sand used was poorly graded.

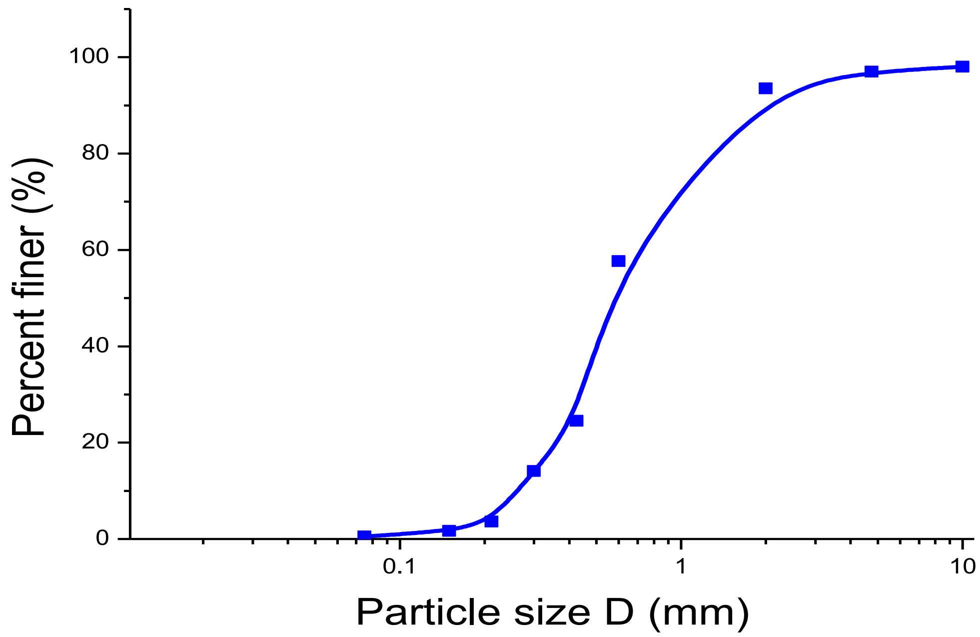

Figure 3.4: Grain size distribution curve of sand

Table 3.2 Properties of sand

Sand Properties	**Value**
Specific Gravity	2.67
D_{10}	0.267 mm
D_{30}	0.438 mm
D_{60}	0.702 mm
Coefficient of Uniformity, C_u	2.63
Coefficient of Curvature, C_c	1.02
Soil Classification	SP

3.4 Compaction test

Standard Proctor method (IS: 2720 Part-7-1980) was used to find maximum dry density and optimum moisture content of different bentonite-sand mixtures with variation in bentonite percent as 10, 20, 25, 30, 40 and 50 % in total weight of the mixture. The compaction mold of diameter 10 cm and height 12.7 cm is used for testing. Total 2.5 kg weight of soil mixture was taken for testing. Bentonite sand mixtures of particular ratio were prepared by taking oven dried bentonite and sand required for that ratio and mixing them to form a homogenous mixture. Distilled water was then added to the mixture and mixed sufficiently to ensure water distribution to all the particles. After the completion of the mixing process, the sample was compacted using standard proctor method. The soil mixture was compacted in three layers, and each layer was given 25 blows with the rammer of 2.6 kg weight with a fall height of 31 cm. The mixing and compaction processes were repeated with an increase in water content of about 2 to 4% of previous value for five to six times. The densities and water contents found were plotted to find the maximum dry density and optimum moisture content of the mixture.

3.5 Permeability test

The permeability of different bentonite-sand mixtures was found using two methods. They were (a) falling head method and (b) consolidation method.

3.5.1 Falling head method

Falling head method is suitable for fine-grained soils having a permeability less than 10^{-5} m/s (IS: 2720 PART 17-1986). Bentonite sand mixtures samples for testing permeability are compacted using standard proctor method in permeameter mold of 10 cm diameter and height 12.7 cm. Bentonite sand mixtures with bentonite percent of 10, 20, 25, 30, 40 and 50% by weight were tested. The samples are compacted at the maximum dry density and optimum moisture content of particular mixture found from standard proctor method. The mold containing the compacted soil mixture was fixed to the base. Filter papers were placed at top and bottom of the soil sample. Soil sample prepared was first saturated and then tested. The apparatus was connected to stand pipe with water. Valves were opened to allow the flow of water through the sample. The initial and final heads were noted along with the time taken for falling of head from initial to final.

The permeability (K) of bentonite-sand mixtures were found using the below formula.

$$K = 2.303 * \frac{aL}{At} * \log(\frac{h_1}{h_2})$$

Where a is standpipe cross-sectional area; A is soil sample cross-sectional area; L is soil sample length; h_1 is initial head of the water; h_2 is final head of the water and t is time taken for fall of the water level.

3.5.2 Consolidation method

Consolidation method was used to find permeability of soil samples less than 10^{-9}m/s. The bentonite-sand mixtures with bentonite percent 30, 40 and 50% by weight were tested in this method. The samples were prepared wet of optimum to have effective compaction (Haug and Wong 1992). The ring of 6 cm diameter and 2 cm height was used to prepare the sample. The sample prepared was placed in consolidometer with filter papers and porous stones at top and bottom of the sample. Incremental loading applied and each load was placed for 24 hours. The dial gauge readings were noted time to time to find the coefficient of permeability.

3.6 Unconfined compressive strength test

Bentonite sand mixtures of bentonite content 25, 30, 40 and 50% by weight were tested for unconfined compression strength characteristics of mixtures. The samples prepared were 3.8 cm diameter and 7.6 cm height. Bentonite sand mixtures were compacted at the maximum dry density and optimum moisture content of the mixtures obtained from compaction tests. Apply the compressive load on the soil sample by turning the handle to give an axial strain rate of about 1% per minute. The reading noted were used to find the unconfined compressive strength of bentonite-sand mixtures

3.7 Swelling pressure test

3.7.1 Modified Oedometer

Modified oedometer is a device developed for conducting swelling pressure test at normal and elevated temperatures. This device consists of two cells inner and outer. Inner cell separates specimen chamber and oil chamber while outer welded to the mild steel base. The heating coil used for temperature elevation surrounds the inner cell. The electric coil connected to an external thermostat for conducting swelling pressure at a higher temperature. Oil chamber filled with industrial grade oil. Thermocouple used to monitor oil reservoir temperature. Oil reservoir closed with a circular steel plate at the top, which connected to an outer cell with screws. Specimen ring consists of compacted soil sample is placed in an inner cell with two porous stones one at the top and other at the bottom of the specimen, and locking collar with locking keys to hold the specimen in place (Tripathy et al. 2015). Two tubes connected at the base of apparatus. Schematic diagram of developed product and modified odeometer with the sample is shown in figure 3.5 and figure 3.6 respectively (Rabbani 2016).

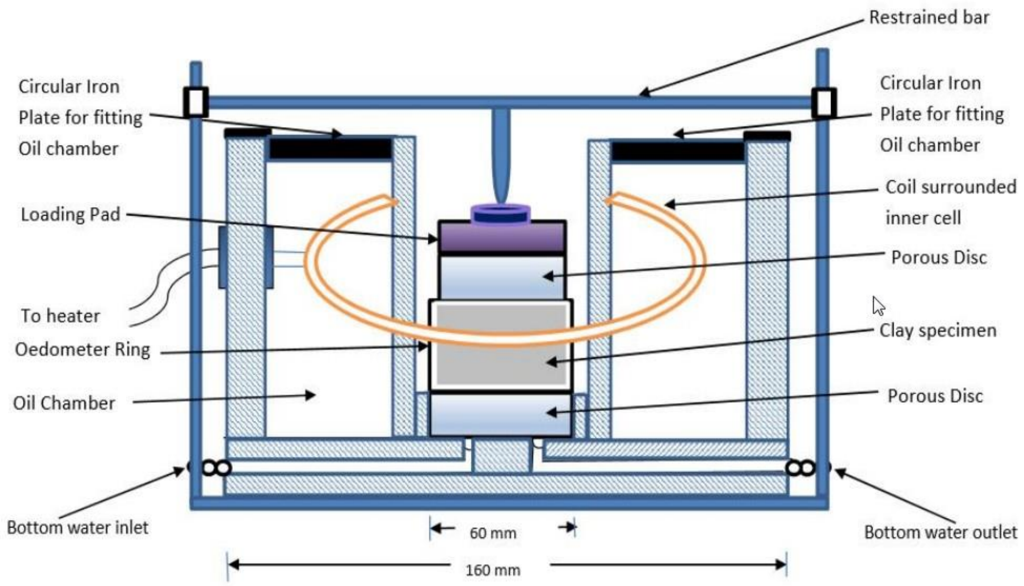

Figure 3.5: Schematic diagram of modified oedometer developed (Rabbani 2016)

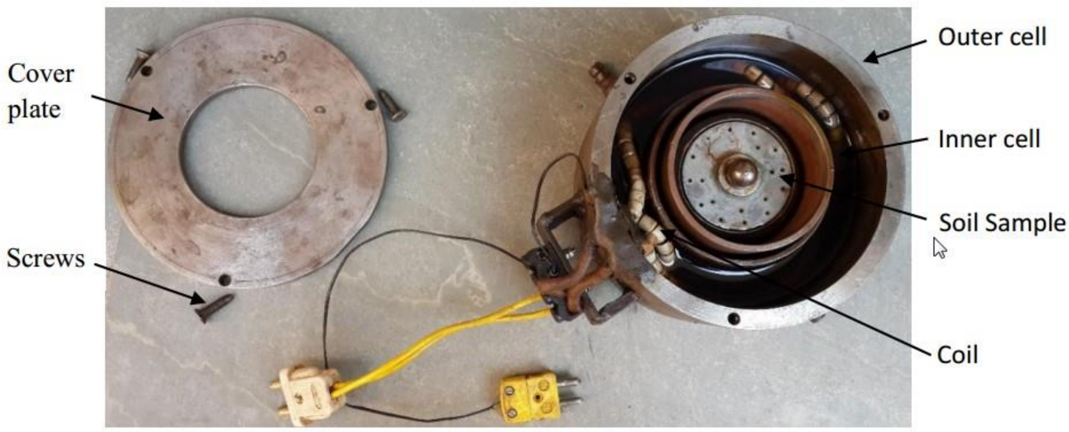

Figure 3.6: Modified oedometer with the specimen (Rabbani 2016)

3.7.2 Experimental setup

Swelling pressure test setup consists of four parts as shown in Figure 3.7: Modified odeometer (testing cell), water reservoir, temperature controller and data logger. The testing cell contains steel base plate, stainless steel specimen ring, two porous stones, the top cover made of mild steel, loading plate, and a pressure sensor. Inlet and outlet at the base for water supply. A load sensor on the sample for load measurement with the time passage.

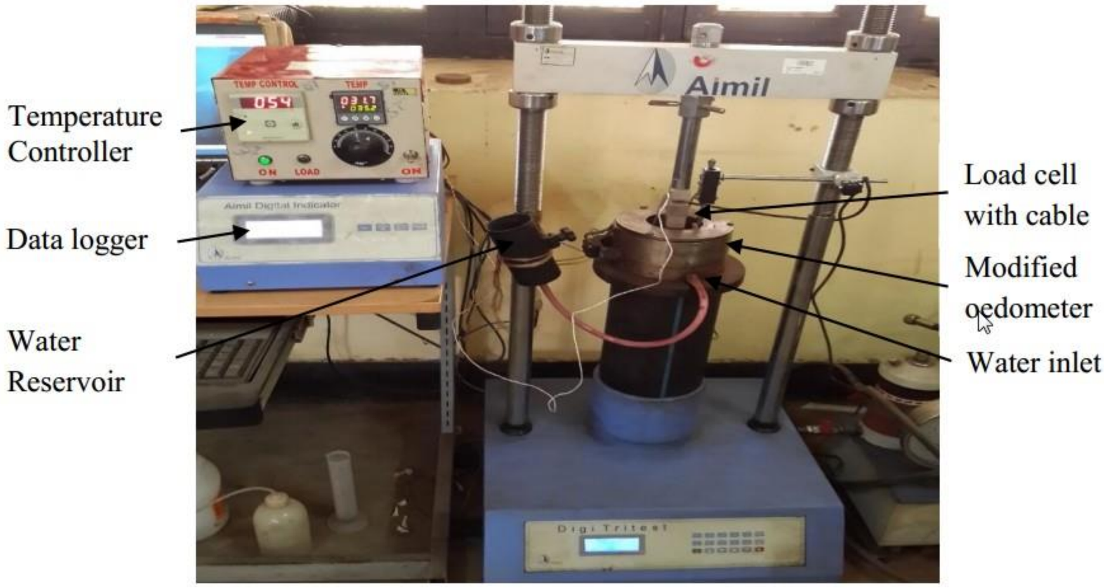

Figure 3.7: Experimental setup for constant volume swelling pressure test (Rabbani 2016)

3.7.3 Constant volume swelling pressure test

Digital strainmeter is used to find swelling pressure of soil sample in constant volume method. Distilled water supplied to bottom of soil sample through the inlet from water reservoir and top of soil sample using laboratory wash bottle. Data obtained used to plot a graph between swelling pressure and time elapsed to find the variation of swelling pressure with the passage of time.

The permeability of 10 and 20% bentonite in bentonite-sand mixtures were very less. Therefore, they were not useful for the purpose of engineering barriers so neglected for further studies. Swelling pressure test conducted for bentonite content of 25%, 30%, 40% and 50% by weight in bentonite-sand mixtures. Soil weight required for testing swelling pressure found using density and volume concept. A cylindrical soil sample of diameter 6 cm and height 2 cm made using cylindrical column mold of diameter 6 cm and height 5.5 cm. Density required for finding the weight of the mixture was the maximum dry density of particular mixture found in standard proctor test. The compressive force was applied to compact the sample with the vertical stress of 35 MPa for 15 minutes. The ring with compacted soil sample placed in modified oedometer with filter papers and porous stones at top and bottom of the soil sample. The modified oedometer placed in loading frame fixed at top and bottom to avoid horizontal movement and to allow only vertical movement (shrink or swell). After setting load value to zero distilled water supplied from the top of sample and inlet for swelling of the sample. The bentonite-sand mixtures start swelling and load cell attached to load frame note the load value automatically with time passage. The swelling test was considered completed once the sample is fully saturated (Villar and Lloret 2004).

Chapter 4
Results and discussions

4.1 Compaction test results

Standard compaction tests were carried out on bentonite-sand mixtures of 10, 20, 25, 30, 40 and 50% bentonite content in total weight of soil mixture. From the compaction test results, dry density moisture content relationship of mixtures was plotted as shown in Figure 4.1. The peak points of compaction curves denote the optimum moisture content and maximum dry density of the mixtures. Table 4.1 shows the maximum dry density and optimum moisture content values of bentonite-sand mixtures. Figure 4.2 and 4.3 show the decrease in maximum dry density and increase in optimum moisture content with increase in bentonite content in mixtures. The reason for the decrease in maximum dry density with increase in bentonite content is due to increase in fine soil thereby increase in surface area. The voids created between fine particles are more compared to coarse particles. Therefore, compaction of fine soil particles leads to the formation of more voids which leads to decrease in dry density. The results obtained are in good agreement with the studies carried out by Chalermyanont and Arrykul (2005), Akgün et al. (2006), Amadi and Eberemu (2012).

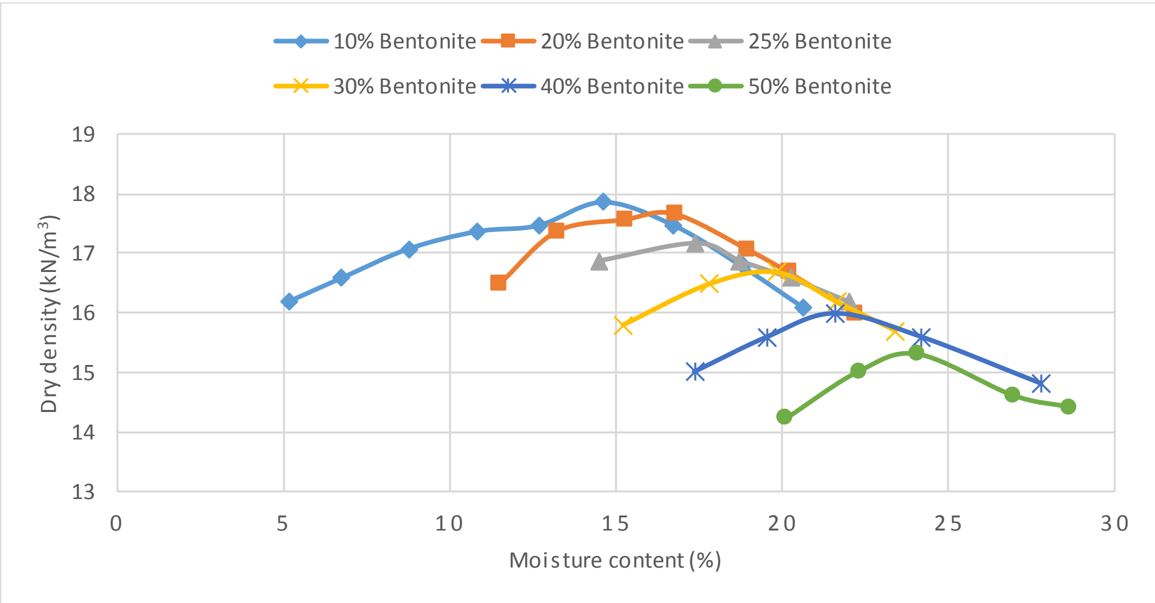

Figure 4.1 compaction curves of bentonite-sand mixtures.

Table 4.1 maximum dry density and optimum moisture content of bentonite-sand mixtures.

Bentonite content (%)	Maximum dry density (kN/m^3)	Optimum moisture content (%)
10	17.85	14.61
20	17.66	16.75
25	17.17	17.4
30	16.68	19.84
40	16	21.59
50	15.3	24.08

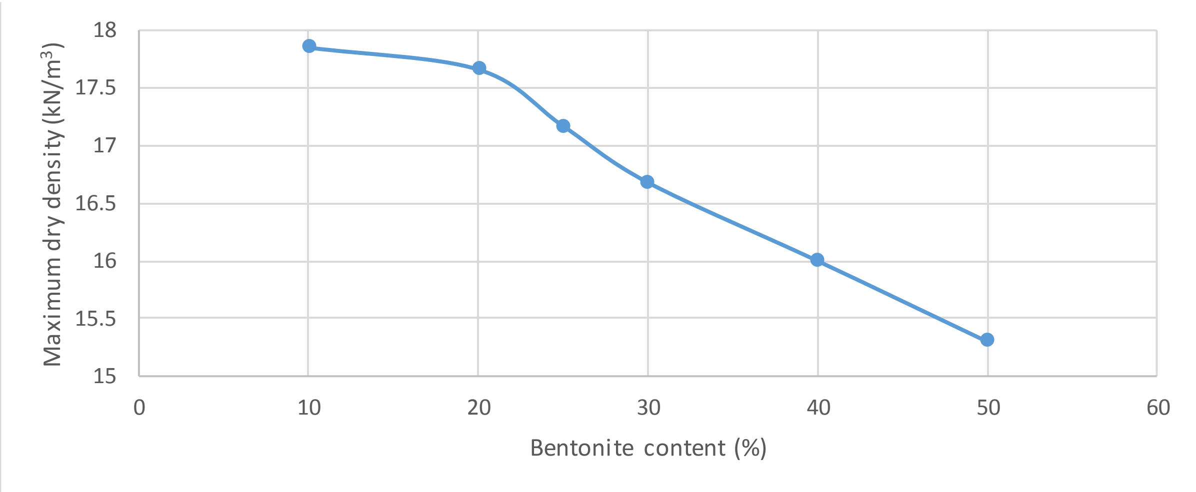

Figure 4.2: Maximum dry density variation with increase in bentonite content

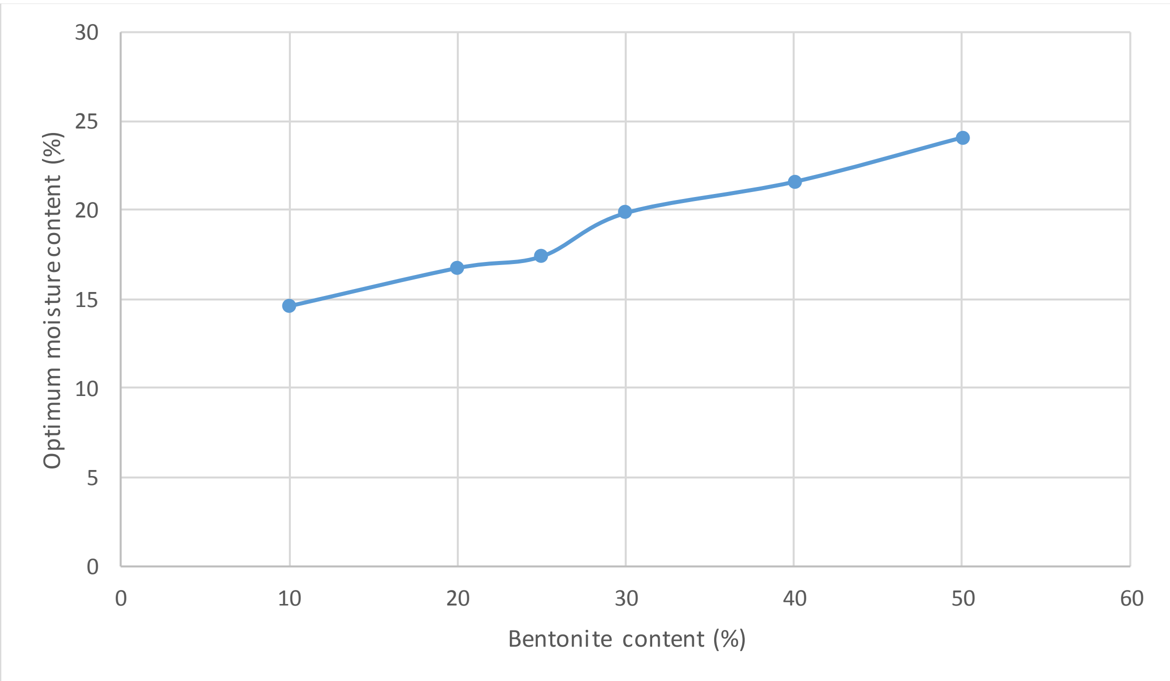

Figure 4.3: Optimum moisture content variation with increase in bentonite content

4.2 Permeability test results

Falling head permeameter tests were carried out on bentonite-sand mixtures of 10, 20, 25, 30, 40 and 50% bentonite content in total weight of soil mixture. The results obtained from the tests were reported in Table 4.2. The permeability values range from $7.09*10^{-6}$ to $0.16*10^{-9}$ m/s for bentonite-sand mixtures of bentonite content varies from 10 to 50%. The results show the decrease of permeability value with increase in bentonite content which is due to swelling nature of bentonite. Many researchers found the decreasing pattern of permeability with an increase in bentonite content (Lee et al. 1994, Borgesson et al. 2002, Siddiqua et al. 2011, Watabe et al. 2011 and Fan et al. 2014).

Table 4.2: Permeability values of bentonite-sand mixtures using falling head method

Bentonite content (%)	Permeability (m/s)
10	7.09×10^{-6}
20	1.08×10^{-8}
25	1.84×10^{-9}
30	0.78×10^{-9}
40	0.39×10^{-9}
50	0.16×10^{-9}

Permeability values less than 10^{-9}m/s were tested using consolidation method. Consolidation tests were carried out on 30, 40 and 50% bentonite-sand mixtures to find permeability values. It was found that there is a variation in permeability values found from both the methods. Variation of void ratio and coefficient of volume compressibility of bentonite-sand mixtures with an increase in pressure are shown in Figures 4.4 and 4.5 respectively. Table 4.3 shows the permeability values of 30, 40 and 50% bentonite-sand mixtures found using consolidation tests.

Table 4.3 Permeability values of bentonite-sand mixtures using consolidation method

Bentonite content	Permeability using consolidation method (m/s)
30	8.736×10^{-9}
40	3.51×10^{-9}
50	1.76×10^{-9}

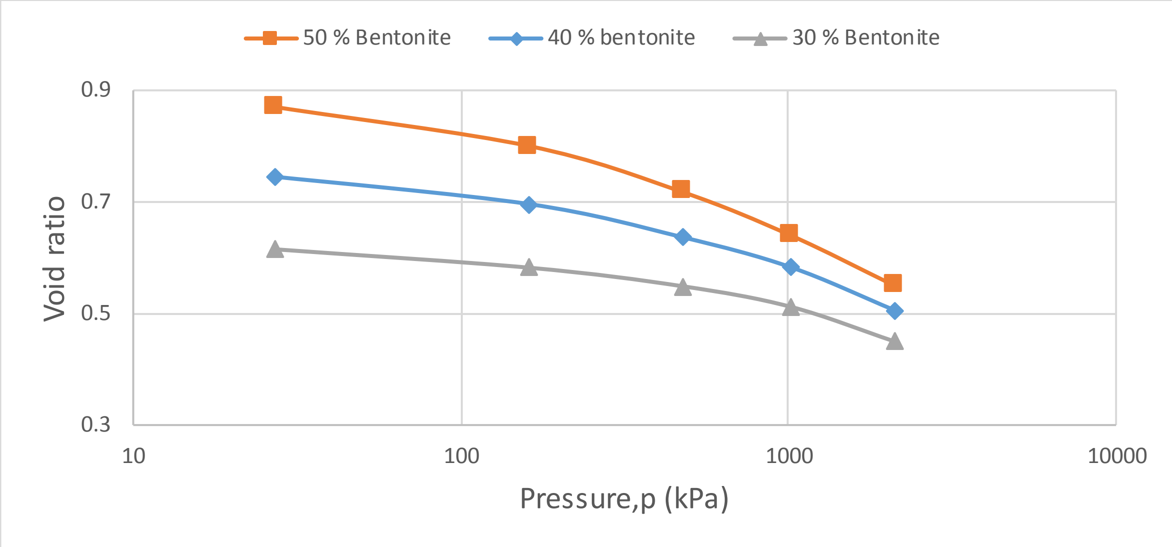

Figure 4.4 Void ratio versus log p of bentonite-sand mixtures

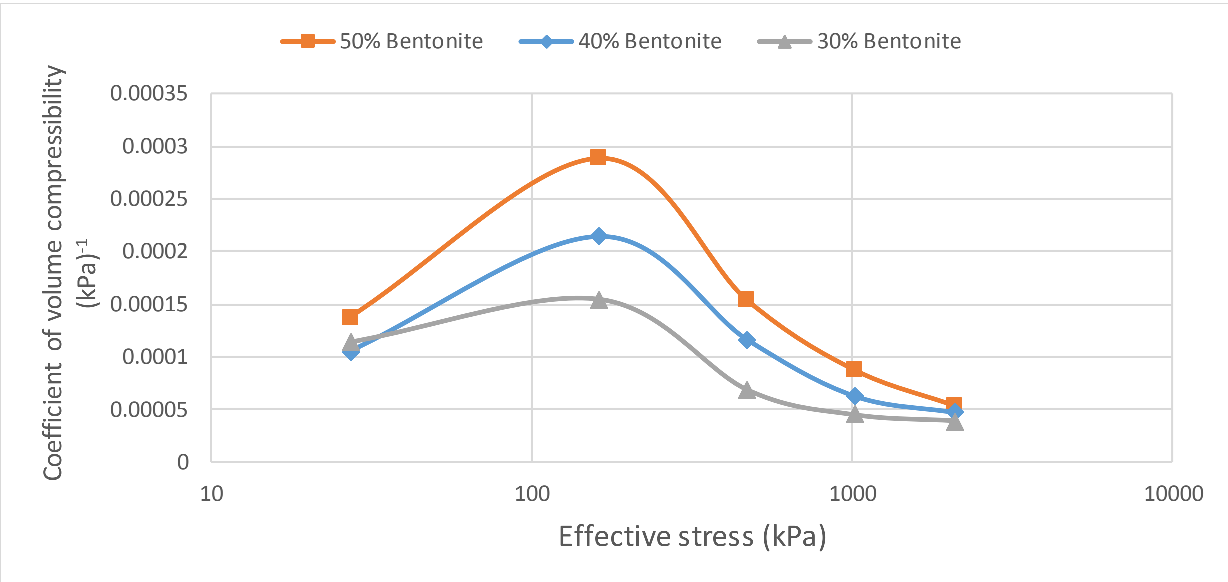

Figure 4.5 m_v versus log p of bentonite-sand mixtures

4.3 Swelling pressure test results

The variation of swelling pressure of bentonite-sand mixtures with time from the initiation of water supply is plotted in Figure 4.6. Initially, there is a rapid increase of swelling pressure with time until it reaches a maximum value. After reaching the maximum swelling pressure, it drops a little and remains almost constant with very little fluctuations. The maximum swelling pressure, final moisture content and degree of saturation of bentonite-sand mixtures are shown in Table 4.4. The variation of maximum swelling pressure with change in bentonite content in mixtures is shown in Figure 4.7.

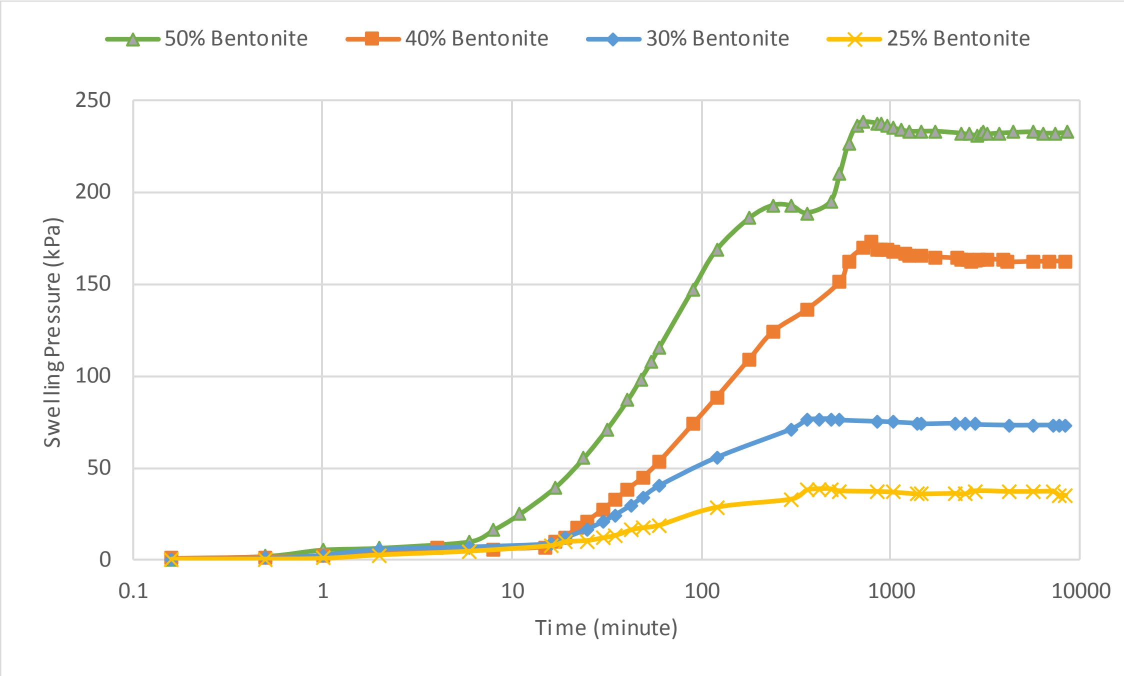

Figure 4.6: Swelling pressure versus time of bentonite-sand mixtures

Table 4.4: Swelling pressure test results of bentonite-sand mixtures

Bentonite (%)	Maximum Swelling pressure (kPa)
25	38.58
30	76.69
40	172.77
50	238.36

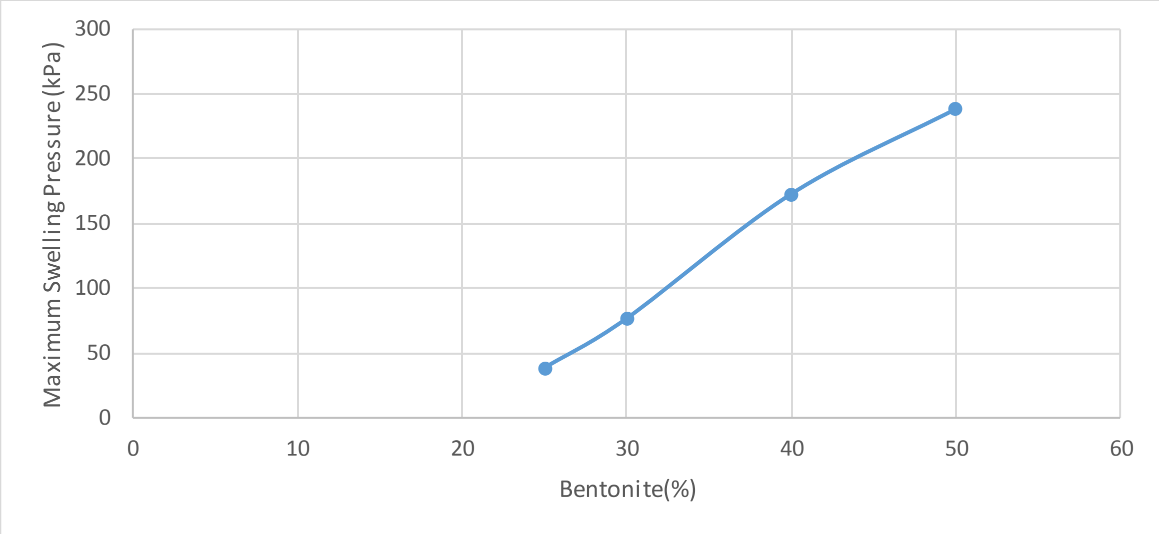

Figure 4.7: Variation of maximum Swelling pressure of bentonite-sand mixtures with an increase in bentonite content.

From Figure 4.7, it was found that maximum swelling pressure increases with increase in bentonite content in the mixture. Figure 4.6 shows swelling pressure increases rapidly at the beginning and reaches a peak followed by an intermediate period where swelling pressure decreases. This intermediate period where swelling pressure decreases or rate of pressure increase in lower usually occurs after 12 to 48 hours of hydration and before the soil sample reaches the full saturation (Ye et al. 2013). When the vertical stress reaches the first peak, the swelling of aggregates induces collapse of soil skeleton under the confined conditions thereby swelling pressure decreases meanwhile soil sample rebuilt its structure and starts swelling again to reach an equilibrium with the continuation of hydration process (Ye et al. 2013). From the Table 4.4, maximum swelling pressure was found when the degree of saturation equal to or more than 93% achieved for all the bentonite-sand mixtures.

4.4 Unconfined compressive strength test results

The results obtained from unconfined compressive strength test for bentonite-sand mixtures are plotted in Figure 4.8. Among the 25, 30, 40 and 50% bentonite-sand mixtures, 40% bentonite-sand mixture has the maximum compressive strength. Table 4.5 shows the maximum unconfined compressive strength and maximum vertical strain of bentonite-sand mixtures. The variation of unconfined compressive strength with bentonite content shown in Figure. From the Figure 4.9, it was found that 40% bentonite-sand mixture is an optimum mixture regarding strength criteria.

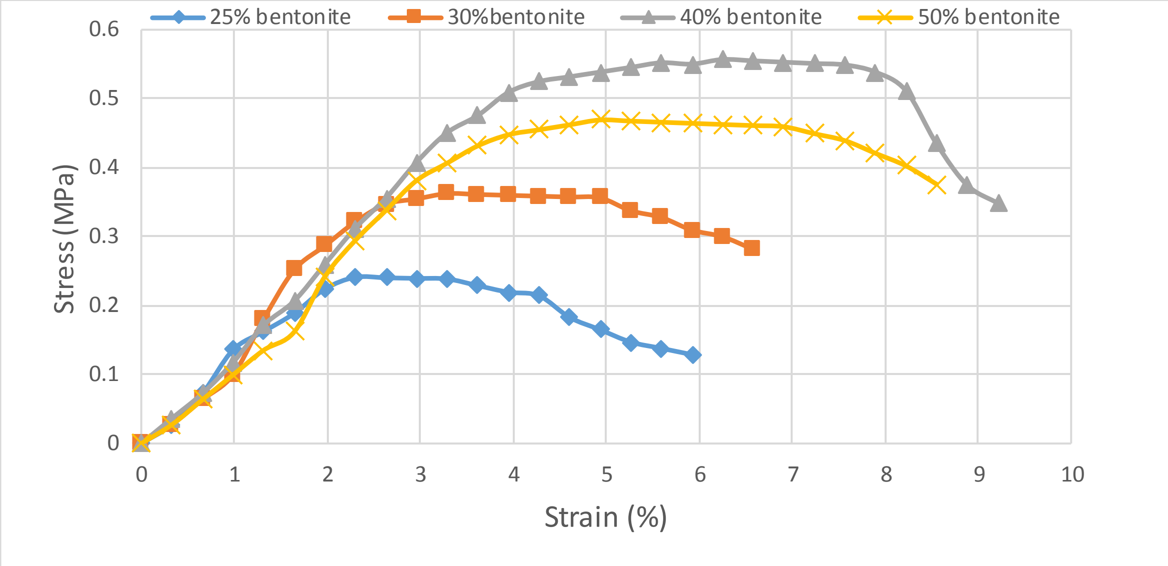

Figure 4.8: Unconfined compressive stress versus strain of bentonite-sand mixtures

Table 4.5: Unconfined compressive test results for bentonite sand mixtures

Bentonite content (%)	Maximum unconfined compressive strength (MPa)	Maximum vertical strain (%)
25	0.24	2.30
30	0.36	3.29
40	0.56	6.25
50	0.47	4.93

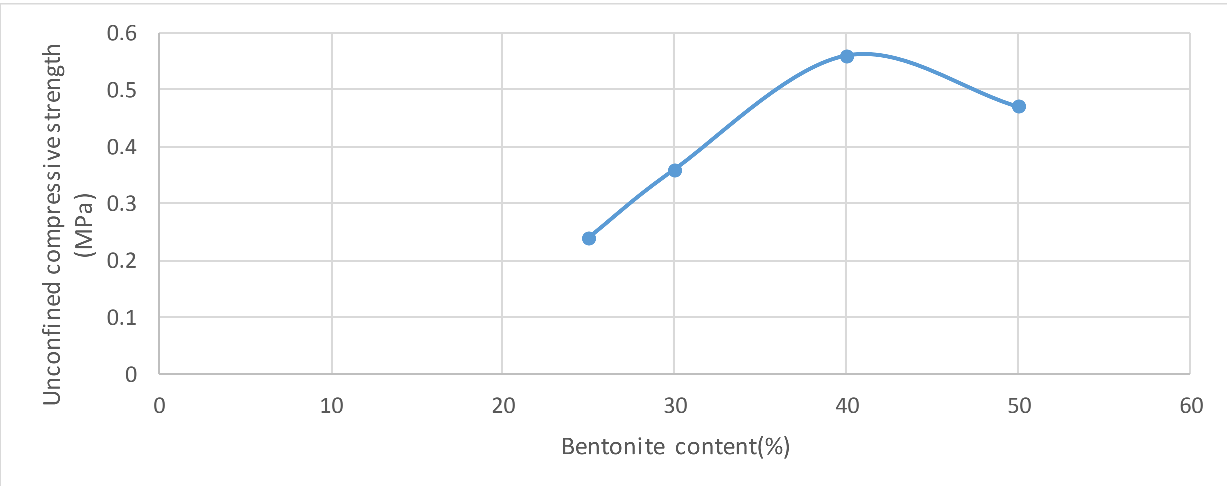

Figure 4.9: Change in unconfined compressive strength with variation in bentonite content.

Chapter 5

Conclusion and scope for further study

5.1 conclusion

Standard compaction tests were conducted on bentonite-sand mixtures with varying bentonite content as 10, 20, 25, 30, 40 and 50% in total weight of the mixture. The permeability of bentonite-sand mixtures compacted at the maximum dry density and optimum moisture content were tested using falling head method. Consolidation method was used to find the indirectly permeability values of mixtures less than 10^{-9} m/s. Swelling pressure test and unconfined compressive strength tests were conducted on mixtures following barrier criteria of permeability range of 10^{-8} to 10^{-10} m/s in the saturated condition.

Based on results maximum dry density and optimum moisture content decreased and increased with increase in bentonite content in the mixture. The permeability of bentonite-sand mixtures decreased with increase in bentonite content in both falling head and consolidation methods. However, there is a variation in results obtained from both the methods. It was due to evaporation effect on water in the standpipe because of longtime taking of experiment in falling head method. Swelling pressure increased with increase in bentonite content in bentonite-sand mixtures because bentonite has montmorillonite that has high swelling nature. Unconfined compressive strength was maximum for 40% bentonite-sand mixture. It increased up to 40% bentonite-sand mixture, and then it decreased.

5.2 Scope for further study

The present study investigated compaction, permeability, swelling and strength characteristics of bentonite-sand mixtures. There is a vast scope to extend further studies on bentonite-sand mixtures as liner/barrier materials. Some of them are

- Investigating the role of temperature in permeability, swelling, compressibility and strength characteristics of bentonite-sand mixtures.
- Investigating the role of different concentrations of salt solutions as pore fluids in permeability, swelling, compressibility and strength characteristics of bentonite-sand mixtures.

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